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Millimeter wave atmospheric turbulence measurements: preliminary results

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Abstract

The effects of atmospheric turbulence on millimeter wave propagation are not as well understood as the corresponding effects on optical propagation, generally because of the strong dependence of turbulence effects on the absolute humidity structure parameter C_Q^2 (as opposed to just the temperature structure parameter C_T^2 and the cross-correlation C_{TQ}) in this frequency range. Scattered results at 35, 94, 140, and 220 GHz are available, but in almost all cases, available atmospheric data are inadequate, generally because turbulence measurements were obtained incidental to other propagation experiments. This paper attempts to compare available results to theory, and shows that agreement in most cases is plausible. An experiment designed to characterize millimeter wave turbulence at several frequencies of interest, while at the same time determining values of appropriate atmospheric parameters, will be discussed. Included in the planned investigation are measurements of the mutual coherence function showing angle-of-arrival effects and intensity fluctuations.

Introduction

The recent increase in interest in the use of millimeter waves for both civilian and military applications has caused emphasis to be placed on the study of the effects of the atmosphere on radiation in this frequency range. Attenuation by oxygen and especially water vapor, scattering by aerosols, and perturbations by atmospheric turbulence are among the subjects being studied at several laboratories in this country and throughout the world. One would expect all of these effects to be different for millimeter waves than for either the microwave or the infrared/visible spectrum because of the peculiar problems associated with the propagation of radiation of intermediate wavelengths through the atmosphere.

In considering atmospheric turbulence at millimeter wavelengths, for example, the contribution of the absolute humidity fluctuations, measured by the structure parameter C_Q^2 , must be considered in addition to the fluctuations in temperature, characterized by the structure parameter C_T^2 . Furthermore, the cross-correlation of these quantities, C_{TQ} , which may be either positive or negative, must also be included in the analysis of millimeter wave turbulence effects. These effects include fluctuations of both intensity and angle-of-arrival, and both of these phenomena will be treated in some detail in this paper.

In the fall of 1978, millimeter wave propagation measurements were made by Georgia Tech at both 94 and 140 GHz at White Sands Missile Range, New Mexico, over a 2 km path¹. Humidity, temperature, and the visible wavelength index of refraction structure parameter C_n^2 were also measured. Significant intensity fluctuations were observed at both frequencies during these tests. These fluctuations could be explained plausibly by a theory of turbulence effects developed by Armand, et al.², who included the effects of the structure functions of both temperature and humidity in their calculations, although the cross-correlation of these parameters was not adequately treated. A treatment including this cross-correlation has been given by Hill, et al.³, whose theory also gives plausible agreement with the White Sands results, as will be shown later. Subsequent measurements were made during winter propagation tests near Burlington, Vermont at frequencies of 35, 95, 140, and 220 GHz^{4,5}. Again, little supporting turbulence related meteorological data are available because turbulence results were obtained incidental to the propagation measurements. However, the observed effects of turbulence showed good agreement with the expected theoretical dependence of the log amplitude variance on both frequency and range, as will be discussed later. The results of these measurements, together with a discussion of their comparison to the theory of Hill, et al. is the main thrust of this paper.

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Since a complete characterization of the atmosphere was not available because of limitations in instrumentation, it was necessary to make some improvisations in the comparison of theory and experiment. For the White Sands measurements, the log amplitude variance was determined from the chart recorder tracings for both the 94 and 140 GHz propagation links. The values of this parameter were then substituted into the equation for log amplitude variance derived by Hill, et al. to deduce the values of the absolute humidity structure parameter C_Q^2 which according to theory would have caused the millimeter wave effects observed. This parameter (along with C_{TQ}) is the only factor in the equation not measured at White Sands. An assumption was made about the relationship between C_Q^2 , C_T^2 , and C_{TQ} that provides a value for the cross-correlation as will be explained later. The result of the calculation is that plausible values for C_Q^2 are obtained. For the Burlington measurements, values of the log amplitude variance σ_y^2 were determined from chart recorder traces for four different frequencies and two different ranges L . For the longer range, σ_y^2 follows the theoretical $L^{11/6}$ variation very well, but the agreement for short path is not as good. The data follow the $L^{11/6}$ range dependence fairly closely. Both sets of measurements will be discussed in more detail in the following sections.

Results of Theory

Hill, Clifford, and Lawrence³ have derived an expression for the log amplitude variance of the fluctuations of electromagnetic radiation propagating through the turbulent atmosphere which holds for microwave through optical frequencies and maintains the dependence on C_Q^2 , C_T^2 , and C_{TQ} . This equation comprises separate contributions from the real and imaginary parts and from the cross-correlation of these parts, as follows:

$$\sigma_x^2 = \sigma_K^2 + \sigma_I^2 + \sigma_{IK} \quad (1)$$

where K , I , and IK refer to the real, imaginary, and cross-correlation contributions, respectively. The real part of σ_x^2 is given by

$$\sigma_K^2 = 0.124k^{7/6}L^{11/6} \left[1 - 2.73 \left(\frac{L_0}{\sqrt{L/k}} \right)^{-7/3} \right] \cdot \left(A_T^2 \frac{C_T^2}{\langle T \rangle^2} + A_Q^2 \frac{C_Q^2}{\langle Q \rangle^2} + 2 A_Q A_T \frac{C_{TQ}}{\langle T \rangle \langle Q \rangle} \right) \quad (2)$$

where k is wavenumber, $\langle T \rangle$ is the mean value of temperature, $\langle Q \rangle$ is the mean value of absolute humidity, and L_0 is the outer scale dimension. The dimensionless parameters A_T and A_Q are given by

$$A_T = \langle T \rangle \frac{\partial N}{\partial T} \bigg|_{P,Q} \times 10^{-6} \quad (3)$$

$$A_Q = \langle Q \rangle \frac{\partial N}{\partial Q} \bigg|_{P,T} \times 10^{-6} \quad (4)$$

where N is the refractivity of the atmosphere. A third equation involving A_P where P is atmospheric pressure must also be considered but pressure fluctuations are shown in Reference 3 to have a negligible effect on refractive index fluctuations at all frequencies of interest. The refractivity N is given by:

$$N = (n-1) \times 10^6 = (77.6 \text{ }^\circ\text{K}/\text{mb}) \frac{P}{T} + (1.71 \times 10^3 \text{ }^\circ\text{K}/\text{g}/\text{m}^3) \frac{Q}{T} \quad (5)$$

where P is in millibars, T is in degrees Kelvin, and Q is in g/m^3 . This equation neglects terms which represent dispersive contributions to the real part of the refractive index in the neighborhood of millimeter wave absorption lines. References 3 and 6 show plots of the refractivity which support the fact that dispersive contributions are at most a few percent in the frequency regions between lines, and therefore they would not have an important contribution to turbulence phenomena. Combining equations (3), (4), and (5) finally gives for A_T and A_Q :

$$A_T = -N \times 10^{-6} \quad (6)$$

$$A_Q = (1.71 \times 10^3 \text{ }^\circ\text{K}/\text{g}/\text{m}^3) \frac{Q}{T} \times 10^{-6} \quad (7)$$

The contributions of the parameters σ_1^2 and σ_{1k} to the log amplitude variance are considered negligible because they contain a parameter B_Q given by:

$$B_Q = \frac{1}{4\pi\nu} \langle Q \rangle \left(\frac{\partial B}{\partial Q} \right)_{T,P} \quad (5)$$

where B is the atmospheric absorption coefficient. In the low-frequency window regions, this parameter is considered negligible, as is borne out by calculations displayed graphically in References 3 and 6.

Finally, it is necessary to devise some sort of value for the cross-correlation term in Equation (2). Hill, et al.³ suggest that an order-of-magnitude estimate for C_{TQ} is

$$\frac{C_{TQ}}{\langle T \rangle \langle Q \rangle} = \pm \left(\frac{C_Q^2}{\langle Q \rangle^2} \frac{C_T^2}{\langle T \rangle^2} \right)^{1/2} \quad (3)$$

assuming a correlation coefficient of ± 1 . For calculations in this paper, the positive sign was chosen because data were taken on sunny days when the surface was a source of both humidity and heat - implying that humidity and temperature fluctuations would have a strong positive correlation.

Using the above results, it is possible to substitute into Equation (2) and calculate values of C_Q^2 based on substituting values of σ_1^2 obtained from chart recorder tracings of field measurements. A later section treats the comparison of values of C_Q^2 determined in this way at 94 and 140 GHz, and also compares the frequency and range dependences of field measurements to those given by Equation (2).

Description of Experiments

Two sets of measurements are used for comparison with theory in this paper, namely the propagation tests mentioned earlier that were conducted at White Sands Missile Range, NM, and those conducted at Burlington, VT. For both sets of tests, meteorological data including temperature, humidity, wind speed and direction, and optical C_n^2 were generally available; but unfortunately many of the sensors for the Burlington measurements were damaged in a storm the night before the measurements were made. Measurements of C_Q^2 and C_{TQ} were not available for either case, which emphasizes a serious need for making dedicated measurements of millimeter wave turbulence effects. Both sets of turbulence data were obtained incidental to other propagation tests. A system designed for making such dedicated measurements is described in Reference 7.

Figure 1 is a sketch of the experimental arrangement used for the White Sands tests, which were conducted at 94 and 140 GHz over a 2 km path in the desert. The transmitters used for both frequencies were free-running klystron oscillators with about 50 mW power output. A precision rotary vane attenuator was used to calibrate several levels of attenuation for the 94 GHz system, but it was necessary to calibrate the 140 GHz attenuation by simply blocking or unblocking the transmitter. The transmitters were 100% modulated with a 1 kHz square wave to facilitate the use of phase sensitive detection. Both transmitter and receiver antennas were horn-lens combinations with beamwidths of 2 degrees for each frequency, and measurements were made simultaneously.

Superheterodyne receivers were used for both frequencies. The 94 GHz receiver used a fundamental mixer with a local oscillator near 94 GHz, while the 140 GHz receiver used a harmonic mixer pumped by a 70 GHz klystron. Phase sensitive detection with lock-in amplifiers was used for both channels, with the 1 kHz reference from the transmitter modulator transmitted over twisted-pair line to the receiver. Under these conditions, it was necessary to reduce transmitted power to avoid saturating the receiver. Receiver outputs were recorded on a dual channel chart recorder.

Two different systems were used to make the Burlington measurements. The first system used transmitter and receiver vans separated by about 600 m, and operated at frequencies of 94, 140, and 220 GHz. The transmitters were based on the pulsed extended interaction oscillator tube built by Varian Canada, and the receivers were simple video detectors. Cassegrain antennas with 60 cm diameters were used for both transmitters and receivers. Unfortunately, the data obtained with this system did not have sufficient gain to permit accurate determinations of the values of σ_1^2 from the recorder tracings. Data from the second system were therefore used for the comparison to be discussed in the next section.

The second system included pulsed radars at 35, 95, 140, and 217 GHz which used IMPATT transmitters and local oscillators. This system used corner cube reflectors at ranges of 152 and 610 m to generate returns and was originally designed to measure absolute atmospheric attenuation at these frequencies. Figure 2 is a schematic diagram of the second system.

Comparison of Theory and Experiment

The measurements made at White Sands Missile Range were divided into a number of separate "events" in which an explosive charge was detonated in the propagation path and the subsequent deterioration of millimeter wave signals was observed at the receiver. Measurements of turbulence effects were necessarily confined to times slightly before and after these events, because the primary purpose of the experiments was to observe propagation through dust. Unfortunately, there were only five events in which both the 94 and 140 GHz systems operated simultaneously well enough to meaningfully compare turbulence effects.

In comparing theory and experiments, measured values of σ_X^2 , P , T , and Q were substituted into Equations (2), (3), (4), and (5) to determine values of C_Q^2 for both 94 and 140 GHz. Table 1 gives values of parameters used to make these calculations. C_T^2 was determined from measurements of optical scintillation by using the relation

$$C_T^2 = \left(\frac{C_n^2}{79P} \times 10^6 \right)^2, \quad (10)$$

where C_n^2 is the visible wavelength index of refraction structure parameter, and P is measured in millibars. Table II gives values of σ_A^2 obtained from chart recorder tracings and values of C_n^2 determined using Equation (10), for each event. Simultaneous data at the two frequencies were not obtained for Events A-1 and B-1, as indicated in the Table. Figure 3 compares C_Q^2 determined in this way from 94 and 140 GHz measurements for each of the five events for which simultaneous data were obtained. The solid curve has unity slope, and all of the points should, of course, lie on this straight line for ideal agreement with theory.

It is also possible to compare measurements of the frequency dependence of the log amplitude variance to theory. The log amplitude variances calculated at the two frequencies are related by

$$\sigma_X^2(140) = \left(\frac{140}{94} \right)^{7/6} \sigma_X^2(94), \quad (11)$$

according to Equation (2). Figure 4 shows the comparison between values of this parameter measured at the two frequencies for the five events. Again, the points should lie on the straight line given by Equation (11).

The variance of angle-of-arrival fluctuations for a spherical wave is given by⁸

$$\sigma_A^2 = 0.54 LC_n^2 r^{-1/3} \quad (12)$$

where r is antenna spacing and σ is measured in radians. Although angle-of-arrival fluctuations were not measured at White Sands, it is of interest to determine their magnitude using values of C_n^2 calculated from Equation (2). In making this determination, note that the factor in parentheses in this equation involving C_T^2 , C_Q^2 , and C_TQ is just the millimeter wave C^2 . Figure 5 is a plot of peak-to-peak (σ_A) angle of arrival fluctuations versus C^2 using values of this parameter derived at 94 GHz. Since σ_A^2 in millimeter wave atmospheric windows is approximately independent of frequency, by Equation (12) neglecting dispersion, the results in Figure 5 may be taken as a representative prediction for millimeter wave windows. Values of C_n^2 are noted on the curve, although this curve is not intended to compare theory and experiment. It is simply intended to show expected values of angle-of-arrival for the observed range of C_n^2 . An antenna spacing of $r=1$ m was used for these calculations.

That the values obtained for C^2 are reasonable can be seen from the following plausibility arguments. If water vapor were thoroughly mixed so that its density fluctuations were driven solely by temperature fluctuations, the following relation would hold

$$\frac{\langle (\delta Q)^2 \rangle^{1/2}}{\langle Q \rangle} = \frac{\langle (\delta T)^2 \rangle^{1/2}}{\langle T \rangle}, \quad (13)$$

and

$$\frac{C_Q^2}{\langle Q \rangle^2} = \frac{C_T^2}{\langle T \rangle^2}$$

or

$$\frac{C_Q^2}{C_T^2} = \frac{\langle Q \rangle^2}{\langle T \rangle^2}.$$

However, in the case of very strong humidity fluctuations³,

$$\frac{\langle(\delta Q)^2\rangle^{1/2}}{\langle Q\rangle} \approx \frac{100 \langle(\delta T)^2\rangle^{1/2}}{\langle T\rangle}$$

or

$$\frac{C_Q^2}{C_T^2} \approx \frac{10^4 \langle Q\rangle^2}{\langle T\rangle^2} \quad (14)$$

Table II gives calculated values of C_Q^2/C_T^2 for each of the events treated. In comparing the average value of this ratio, which is $0.55 \text{ g}^2/\text{m}^6 \cdot \text{K}^2$, to the average value of $\langle Q\rangle^2/\langle T\rangle^2 = 8.65 \times 10^{-4} \text{ g}^2/\text{m}^6 \cdot \text{K}^2$ in Table I, one obtains

$$\frac{C_Q^2}{C_T^2} \approx 640 \frac{\langle Q\rangle^2}{\langle T\rangle^2}, \quad (15)$$

which is a reasonable result, indicating that the values of C_Q^2 obtained in this way are plausible.

Finally, the frequency and range dependences of σ_χ^2 measured at Burlington were compared to experiment at 35, 95, 140, and 217 GHz. Values of σ_χ^2 obtained from the chart recorder tracings are plotted as a function of frequency for the 610 m path in Figure 6. The best-fit curve having a $\nu^{1/6}$ dependence was drawn through these points (virtually a straight line). A change in σ_χ^2 corresponding to $(L_2/L_1)^{11/8}$ was then scaled downward on the graph, and a second straight line was drawn parallel to the first. Values of σ_χ^2 for a range of 152 m were plotted on this graph. As seen in the figure, the agreement with the $\nu^{1/6}$ dependence is very good for the longer path, but not as good for the shorter. It is possible that near-field effects contributed to errors in the latter data. Also, these data were unaccountably noisier than the long path data. However, Figure 6 shows that the agreement between theory and experiment for the frequency and range dependencies of σ_χ^2 is generally good.

Future Measurements

A dedicated millimeter wave turbulence measuring facility with several appropriate meteorological sensors is being assembled by Georgia Tech and NOAA with support from the U.S. Army Research Office. This system will consist of bistatic transmitter and receiver systems housed in trucks and will probe all of the atmospheric windows and absorption lines in the range 118 GHz to 340 GHz.

The transmitter will be a phase-locked klystron oscillator with an offset paraboloid antenna mounted in a step-van. Four receivers with separations varying from 1.4 to 10 m and pumped by a single local oscillator will be used to measure turbulence induced phase and amplitude fluctuations, from which the atmospheric mutual coherence function can be derived. These results will also give the log amplitude variance and the magnitudes of phase fluctuations from which the angle-of-arrival of the transmitted wavefront can be determined. The receivers will be mounted in a semi-trailer van and will use horn-lens antennas. Power from the single phase-locked klystron local oscillator will be distributed to the four receiver mixers by a system of optical beam splitters and beam waveguides. The propagation path is expected to be about 2 km in length.

A complete set of meteorological instrumentation will provide atmospheric data coincident with the measured phase and amplitude fluctuations. Measurements of C_T^2 , C_Q^2 , C_{TQ} , temperature, humidity, wind speed and direction, and aerosol parameters will be made. Data acquisition and some limited preprocessing will be accomplished by a microprocessor-based computer system, which will simultaneously store atmospheric parameters and turbulence data on tape. Provision is also being made to record measured results on chart recorders and CRT terminals to continuously monitor the data acquisition process.

This facility is expected to be operational in the fall of 1982 with frequency coverage from 118-174 GHz, with the other frequencies being added later. Reference 7 gives a detailed description of this measurement system.

Conclusions

This paper compares theory to experiment based on two sets of millimeter wave propagation measurements obtained with limited meteorological data. Agreement in all cases is generally good, but it is again emphasized that dedicated millimeter wave turbulence measurements must be made before realistic conclusions can be drawn. At the present time, only scattered data are available. The millimeter wave turbulence measuring facility discussed briefly in the preceding section is designed to meet the need for more detailed, dedicated measurements.

Due to the nature of the measurements discussed in this paper, some care should be taken in relating them to actual situations or in using them to design millimeter wave systems. Although the agreements achieved have been generally good, they may be fortuitous. It does appear, however, that the magnitudes of the effects are great enough so that turbulence should be considered in the design of millimeter wave systems.

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Table I

Parameters Used in Calculations
Based on White Sands Data

Frequencies	94 and 140 GHz
Path Length L	2 km
Outer Scale Dimension L_0	2.5 m
A_T	-3.22×10^{-4}
A_Q	5.03×10^{-5}
$\langle T \rangle$	289°K
$\langle Q \rangle$	8.5 g/m^3
C_T^2	Calculated from Optical C_n^2
C_Q^2	Calculated
σ_A^2	Determined from Recorder Tracings

Table II

Values of C_T^2 , σ_A^2 , and C_Q^2/C_T^2

Events	$C_T^2 (^{\circ}\text{K} - \text{m}^{-2/3})$	σ_A^2	$C_Q^2/C_T^2 (\text{g}^2/\text{m}^6 - ^{\circ}\text{K}^2)$
		94 GHz	140 GHz
A-1	0.109	1.19×10^{-3}	0.77
B-1	0.545		1.20×10^{-4}
B-3	0.163	9.32×10^{-4}	1.14×10^{-3}
B-4	0.0436	2.12×10^{-4}	3.76×10^{-4}
B-6	0.0218	1.86×10^{-4}	4.96×10^{-4}
D-1	0.0654	2.66×10^{-4}	3.12×10^{-4}
D-2	0.00654	1.46×10^{-4}	2.12×10^{-4}

Note: Values of C_Q^2/C_T^2 were calculated by dividing C_Q^2 , determined by averaging 94 and 140 GHz results, by C_T^2 .

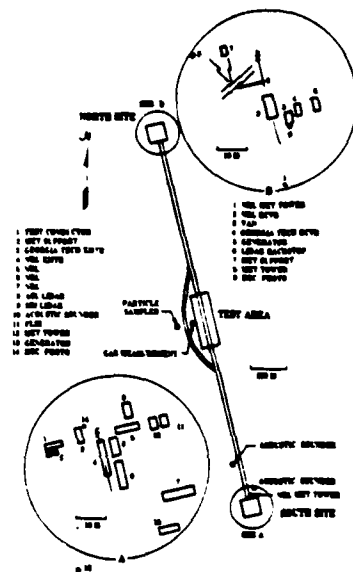


Figure 1. Plan View of Experimental Arrangement Used for White Sands Tests.

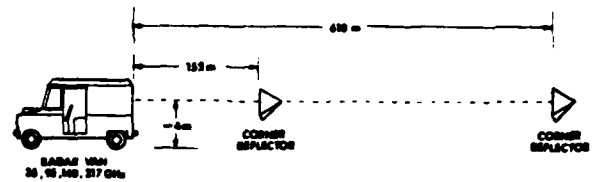


Figure 2. Schematic of Burlington Tests.

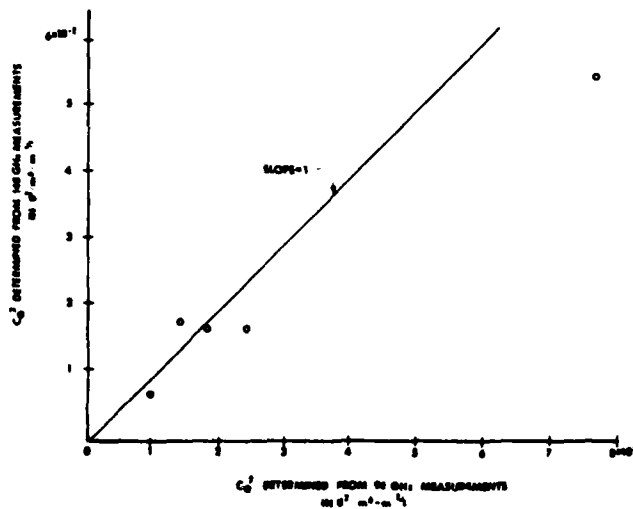


Figure 3. Comparison of C_O^2 Determined from 94 and 140 GHz Measurements.

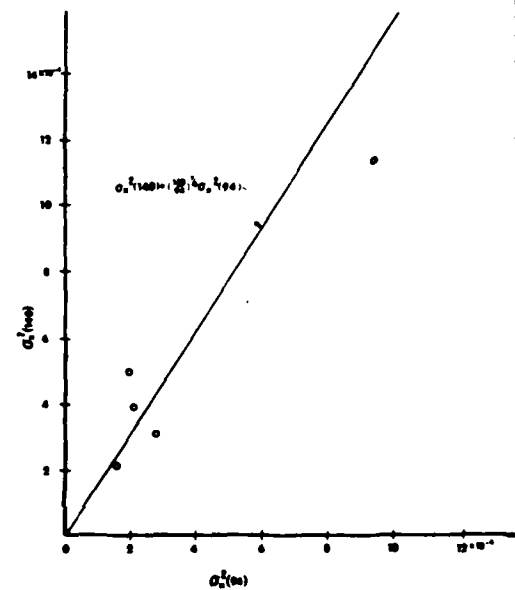


Figure 4. Comparison of σ_X^2 Determined from 94 and 140 GHz Measurements.

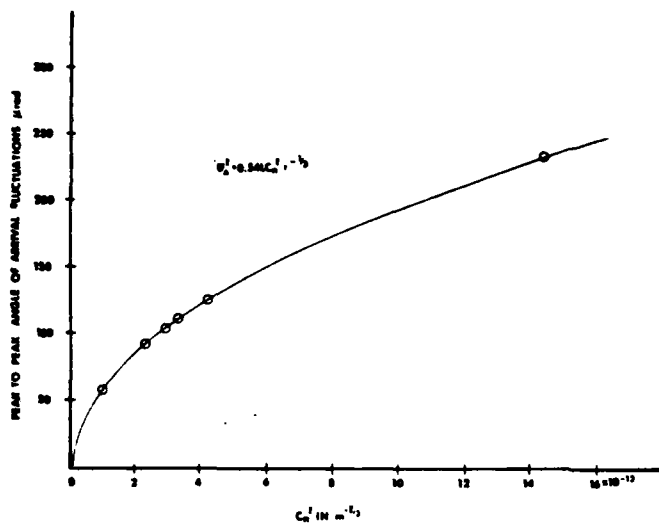


Figure 5. Calculated Peak-to-Peak Angle-of-Arrival Fluctuations.

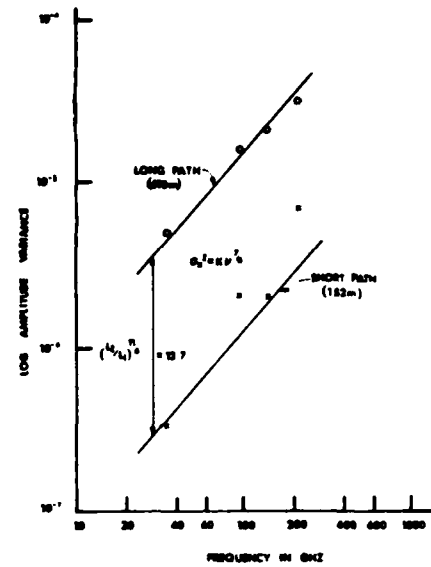


Figure 6. Comparison of the Frequency and Range Dependence of Turbulence Measurements to Theory.



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